Appendix A

Variables and Parameters Used in WinDS

Variable	Units	Description
a_j	fraction	The fraction of existing transmission line j capacity available to wind
BASE_ELEC	MW	The national electrolyzer capacity at the start of the period
BASE_FCELL	MW	The national fuel cell capacity at the start of the period
BASE_SMR	Kg/year	The national SMR capacity at the start of the period
BASETPCA	MW	The national transmission capacity at the start of the period
BASE_WIND	MW	The national wind capacity at the start of the period
$BASE\_WINDinst_i$	MW	The region i wind capacity at the start of the period
$btech_q$		A binary parameter that is 1 if q is a base-load technology and 0 otherwise
c	integer	Subscript indicating the wind class
C		Generation from all conventional power plants that deliver power to NERC region r
$CAOMH_{\text{technology name}}$	$/kWh or $/kg	Present value of the variable O&M cost (including any production tax credit) for a unit of production (for hydrogen or storage technologies) in each year of the evaluation period
Carboncost	($/pound carbon)	Cost of carbon emissions
carbtaxmax	$/ton carbon	Ultimate carbon tax level
ctaxdiscsum		Multiplier to convert annual cost of carbon to present value cost over the evaluation period
CCC_q	$/MW	The turnkey capital cost per MW of plant type q
$CCH2_{\text{technology name}}$	$/MW or $/(kg/year)	Capital cost of a hydrogen or storage technology
$CCONVF_q$	$/MW	The present value over the evaluation period of the fixed O&M costs of plant type q
$CCONV_q$	$/MW	The capital cost of plant type q after accounting for taxes and finance
$CCONVV_{n,q}$	$/MWh	The present value of the variable operating and fuel costs for one MWh in each of E years in PCA n for technology q

$CCT_{n,p}$	\$/MWh	The present value of transmitting 1 MWh of power for each of E years between PCA's n and p
CF_c	fraction	Annual capacity factor of new onshore wind systems of class c in the time period being run
$CFcofd_c$	fraction	Annual capacity factor of new deep offshore wind systems of class c in the time period being run
$CFcofs_c$	fraction	Annual capacity factor of new shallow offshore wind systems of class c in the time period being run
$CF\_corr_{c,i,m}$	fraction	Correction to the annual capacity factor for onshore wind for class c in region i for each time slice m
$CF\_corrofd_{c,i,m}$	fraction	Correction to the annual capacity factor for deep offshore wind for class c in region i for each time slice m
$CF\_corrofs_{c,i,m}$	fraction	Correction to the annual capacity factor for shallow offshore wind for class c in region i for each time slice m
$CF\_corrps_{c,i,s}$	fraction	Correction to the annual capacity factor for onshore wind for class c in region i for the peak time slice in season s
$CF\_corrpsofd_{c,i,s}$	fraction	Correction to the annual capacity factor for deep offshore wind for class c in region i for the peak time slice in season s
$CF\_corrpsofs_{c,i,s}$	fraction	Correction to the annual capacity factor for shallow offshore wind in region i for class c for the peak time slice in season s
$CF\_corrs_{c,i,s}$	fraction	Correction to the annual capacity factor for onshore wind for class c in region i for season s
$CF\_corrsofd_{c,i,s}$	fraction	Correction to the annual capacity factor for deep offshore wind for class c in region i for season s
$CF\_corrsofs_{c,i,s}$	fraction	Correction to the annual capacity factor for shallow offshore wind for class c in region i for season s
$CfixOMH_{technology\ name}$	\$/MWh or \$/kg H_2	Fixed O&M cost for a unit of production capacity (for hydrogen or storage technologies)
$CFO_{c,i}$	fraction	Average capacity factor of all existing (at the start of the current period) class c onshore wind on existing (at the start of the analysis time frame) lines in region i

$CFofs_c$		Capacity factor for new shallow offshore wind at a class c site
$CFofd_c$		Capacity factor for new deep offshore wind at a class c site
$CFOofd_{c,i}$	fraction	Average capacity factor of all existing (at the start of the current period) class c deep offshore wind on existing (at the start of the analysis time frame) lines in region i
$CFOofs_{c,i}$	fraction	Average capacity factor of all existing (at the start of the current period) class c shallow offshore wind on existing (at the start of the analysis time frame) lines in region i
$CFTO_{c,i}$	fraction	Average capacity factor of all existing (at the start of the current period) class c onshore wind on new (built in this period) lines in region i
$CFTOofd_{c,i}$	fraction	Average capacity factor of all existing (at the start of the current period) class c deep offshore wind on new (built in this period) lines in region i
$CFTOofs_{c,i}$	fraction	Average capacity factor of all existing (at the start of the current period) class c shallow offshore wind on new (built in this period) lines in region i
$CGelectroyzer_{hebp}$	\$/MW	Increase in electrolyzer price over cost in growth bin hebp, due to rapid growth in electrolyzer deployment
$CGFC_{hfcbp}$	\$/MW	Increase in fuel cell price over cost in growth bin hfcbp, due to rapid growth in fuel cell deployment
CG_g	\$/MW	Increase in turbine price over cost in growth bin g, due to rapid growth in wind deployment
$CGinst_{ginst}$		Increase in wind installation price over cost in growth bin ginst, due to rapid growth in wind deployment
Cgridconnect	\$/MW	The cost of connecting a generator to the grid – excludes transmission spur cost
$CGSMR_{hsmrbp}$	\$/MW	Increase in steam methane reformer price over cost in growth bin hsmrbp due to rapid growth in steam methane reformer deployment
$cheatrate_q$	MBtu/MWh	Heat rate for generator type q
$CHEFF_{technology\ name}$	MWh/kg or kg/MWh or kg/MBtu	Efficiency of hydrogen/storage

CIL_{ilg}	$/MW	Present value of the additional cost of interruptible load beyond the base cost (see CILA) in step ilg of the interruptible load supply curve
CIL_n	$/MWh	Present value over the evaluation period of the base cost of interruptible load in PCA n
CILA	$/MW	CILA is read in as the annual base cost of one MW of interruptible service and is converted to the present value of the base cost of one MW of interruptible service purchased in each year of the evaluation period
$CIL\_SC(ILBP_k)$	fraction	The fractional breakpoint associated with step k of the supply curve
$class_{c,i}$		Binary parameter that indicates whether class c onshore wind in region i that uses existing (at the start of the analysis time frame) transmission is the best onshore wind to consider in this time period
$classofd_{c,i}$		Binary parameter that indicates whether class c deep offshore wind in region i that uses existing (at the start of the analysis time frame) transmission is the best deep offshore wind to consider in this time period
$classofs_{c,i}$		Binary parameter that indicates whether class c shallow offshore wind in region i that uses existing (at the start of the analysis time frame) transmission is the best shallow offshore wind to consider in this time period
$classT_{c,i}$		Binary parameter that indicates whether class c onshore wind in region i that uses new (installed in this time period) transmission is the best onshore wind to consider in this time period
$classTofd_{c,i}$		Binary parameter that indicates whether class c deep offshore wind in region i that uses new (installed in this time period) transmission is the best deep offshore wind to consider in this time period
$classTofs_{c,i}$		Binary parameter that indicates whether class c shallow offshore wind in region i that uses new (installed in this time period) transmission is the best deep offshore wind to consider in this time period
$Coal\_old\_prev_{n,q}$	MW	The capacity of coal-fired generation in PCA n of type q at the end of the previous two-year period

Coal_old_prev$_{coal-old-1,n}$	MW	The capacity of coal-fired generation with scrubbers that existed before the analysis time frame in PCA n that was still operating at the end of the previous two-year period
Coal_old_prev$_{coal-old-2,n}$	MW	The capacity of coal-fired generation without scrubbers that existed before the analysis time frame in PCA n that was still operating at the end of the previous two-year period
coalowsul$_{n,coal-old-1}$	MWh	Total conventional generation from coal-fired generation with scrubbers that existed before the analysis time frame in PCA n using low-sulfur coal
coalowsul$_{n,coal-old-2}$	MWh	Total conventional generation from coal-fired generation without scrubbers that existed before the analysis time frame in PCA n using low sulfur coal
coalowsul$_{n,q}$	MWh	Total conventional generation from coal plants of type q in PCA n using low-sulfur coal
coallowsulinccost$_n$	$/MMBtu	The additional cost of low sulfur coal relative to high-sulfur coal in PCA n
coallowsulpolred	tons/MWh	The delta (tons) in SO_2 emissions per MWh between high sulfur and low sulfur coal
COMF$_q$	$/MW-yr	The annual fixed O&M cost for plant type q
CONSF$_t$	fraction	The fraction of the capital cost in year t of construction
CONTRACTCAP$_{n,p}$	MW	The electric capacity contracted by PCA p to be received from PCA n
CONVCAP$_{n,q}$	MW	A variable for the capacity of generator type q installed in PCA n
CONVCAPC$_q$	MW	The effective load-carrying capability of conventional capacity type q
CONVCAP$_{in,q}$		The existing conventional capacity in interconnect in of type q
CONVGEN$_{m,n,q}$	MW	A variable for the capacity of generator type q operating during time slice m in PCA n
CONVPGEN$_{m,n,q}$	MW	A variable for the capacity of generator type q operating in peak time slice m in excess of the generation by type q in non-peak time slices (CONVPGEN$_{m,n,q}$ will be zero for off-peak time slices).
CONVOLD$_{n,q}$	MW	Capacity in PCA n of generator type q at the end of the previous time period
CONVpol$_{pol,q}$	Lb/MWh or ton/MWh	Emission of pollutant pol with each MWh of generation by technology q
CONVRET$_{n,q}$	MW	The capacity in PCA n of generator type q

		retired in this period.
$CONVRETkn\_pgas_n$		The levelized cost of power from a natural gas combined-cycle plant in PCA n
$CONVT_{m,n,p}$	MW	Variable for the conventional capacity in time slice m transmitted from PCA n to PCA p
$CORR_{c,i,cc,ii,r}$		The correlation between class c wind in region i and class cc wind in region ii.
$COVAR_{c,i,cc,ii,r}$		The covariance between class c wind in region i and class cc wind in region ii
costinstfrac	fraction	The fraction of the capital cost of wind associated with installation
CP		The construction period
$cpop_{c,i}$		A multiplier on the capital cost of transmission lines for wind to account for increased siting/land costs in highly populated areas. The value varies between 1 and 2 as a linear function of population density in the vicinity of class c wind sites in region i
CQS	$/MW	The cost to modify a combustion turbine to provide a quick-start capability
$CRF_{d,E}$		The capital recovery factor computed at discount rate d for E years, i.e. the fraction of the capital cost of an investment that must be returned each year to earn a rate of return equal to d if income taxes and financing are ignored
$cslope_{c,i}$	degree	Terrain slope for class c wind sites in region i
cslopeTcostfactor		Fractional increase in transmission capital cost for each degree of terrain slope
cslopeWcostfactor		Fractional increase in wind capital cost for each degree of terrain slope
$CSRV_{n,q}$	$/MWh	The present value over E years of the operating and fuel cost of spinning reserve in PCA n of type q
cur_year		The first year of the two-year period for which the optimization is being performed. Cur_year is always the even-numbered year
$CvarOM_q$	$/MWh	The variable O&M cost for technology q
CW_c	$/MW	Capital cost of class c onshore wind including cost reductions through learning-by-doing, and the present value of taxes and financing
$CWcofs_c$	$/MW	Capital cost of class c shallow offshore wind including cost reductions through learning-by-doing, and the present value of taxes and

		financing.
CWcofd$_c$	$/MW	Capital cost of class c deep offshore wind including cost reductions through learning-by-doing, and the present value of taxes and financing.
CWOMc	$ / MW	The present value of E years of fixed and variable operating costs for class c onshore wind including production tax credits
CWOMcofs$_c$	$ / MW	The present value of E years of fixed and variable operating costs for class c shallow offshore wind including production tax credits
CWOMcofd$_c$	$ / MW	The present value of E years of fixed and variable operating costs for class c deep offshore wind including production tax credits
d	fraction	Discount rate
Depf$_t$	fraction	Depreciation fraction in year t
DEretper		The period during which the older remaining (i.e, not yet retired) distributed electrolyzers were constructed
DISFCELL_CAP$_n$	MW	Variable for new distributed fuel cell capacity within PCA n using hydrogen from distributed electrolyzers
DISFCELL_CAP_OLD$_{n,t}$		Distributed fuel cell capacity built in PCA n in period t using hydrogen from distributed electrolyzers
dis$_{i,j}$	miles	Distance between the center of regions i and j
dis$_{p,n}$	miles	Distance between the center of PCAs p and n
d$_n$	fraction	Nominal discount rate
DP	years	Depreciation period for income tax purposes
d$_r$	fraction	Real discount rate
E	years	The evaluation period or investment lifetime
Ecostescal$_{n,q}$		Annual real price escalation of fuel used by technology q in PCA n
EGR(HEBP$_k$)		Breakpoints that discretize the growth price penalty
ELE$_i$	MW	Variable for the new storage conversion (e.g., electrolyzers/hydrogen storage) capacity at the onshore wind site in region i
fcellcapacity$_i$	MW	Variable for new generator (e.g., fuel cell) capacity fueled by the storage medium (e.g., hydrogen) produced from onshore wind in region i

fcelldest$_{n,s}$	MWh	Variable for electricity consumed in PCA n in season s generated from generators (e.g., fuel cells) fueled by stored energy (e.g., hydrogen) from new wind
fcelldestold$_{n,s}$	MWh	The generator (e.g., fuel cell) output in season s from wind-sited generators fueled by stored energy (e.g., fuel cells) built in previous periods that ship power to PCA n
fcell_inregion$_{c,j,s}$	MWh	Variable for electricity generated from new generators fueled by stored energy (e.g., fuel cells fueled by hydrogen) from new class c wind resources in wind supply region j for use in the same wind demand region j during season s
fcell$_{i,r,s}$	MWh	Variable for electricity generated from new generators fueled by stored energy (e.g., fuel cells using hydrogen) from wind in wind supply region i for use in NERC region r during season s
FCretper		Period during which the older remaining (i.e. not yet retired) fuel cells were constructed
FCGR(HFCBP$_k$)		Breakpoints that discretize the fuel cell growth price penalty
FF	fraction	Fraction of the capital cost of a plant that is financed
Fo$_q$	fraction	Forced outage rate for generator type q
Fprice$_{q,n}$	$/MMBtu	The cost of the input fuel
GPElec		The growth penalty for electrolyzers for each percent growth above the breakpoint
GPFC		The growth penalty for fuel cells for each percent growth above the breakpoint
GPSMR		The growth penalty for steam methane reformers for each percent growth above the breakpoint
Gt$_g$	fraction	A fractional multiplier on the national wind capacity that defines the national wind capacity in step g of the wind turbine price multiplier for rapid growth
Gtinst$_{ginst}$	fraction	A fractional multiplier on the wind capacity in a region that defines the region's wind capacity in step ginst of the wind installation price multiplier for rapid growth
grid_2_welectrolysis$_{i,m}$	MWh	Grid-supplied electricity to new storage (e.g., electrolyzers/hydrogen storage) at grid-connected wind farms in region i in time slice m

grid_2_welectrolysis_inregion$_{i,m}$	MWh	Grid-supplied electricity to new storage (e.g., electrolyzers/hydrogen storage) at wind farms in region i in time slice m whose electric generation is used within the region
H2energy		Annual production of energy for storage (e.g., hydrogen)
H2energy_summerday		Energy produced for storage during a summer day (e.g., hydrogen)
H2_loadprofile$_m$	fraction	Fraction of annual hydrogen production from nonwind production technologies that occurs in time slice m
h2stored_summerday$_i$		Energy storage capacity (e.g., electrolyzers/hydrogen storage) required to meet the on-peak operation of the generators operated from storage (e.g., fuel cells) at wind sites in region i
H2PRICE	$/kg	Price that hydrogen will receive in the marketplace in this time period
H2_prodnhours		The number of hours that nonwind hydrogen production facilities are operated each year
H2storagecapacity$_i$		Variable for new hydrogen storage capacity in region i
H3		The peak time slice in the summer season
HEGBIN$_{hebp}$	MW	Variable for new national storage-conversion process (e.g., electrolyzer) capacity in growth bin hebp
HEGBINCAP$_{hebp}$	fraction	Fractional growth in national storage-conversion process (e.g., electrolyzer) capacity in growth step hebp
He$_n$	MWHr	Annual hydro energy available in PCA n
HFCGBIN$_{hfcbp}$	MW	Variable for new national generator capacity fueled from storage (e.g., fuel cell) in growth bin hfcbp
HFCGBINCAP$_{hfcbp}$	fraction	Fractional growth in national conversion-storage capacity (e.g., electrolyzer/hydrogen storage) in growth step hfcbp
hfdemand$_j$	Kg/year	Maximum annual demand for hydrogen as a transportation fuel for light-duty vehicles in region j in the base year
hfdemand_escal	fraction	Annual escalation in the demand for light-duty vehicle fuels
hfd$_j$	kg	Variable for hydrogen fuel produced by new wind installations connected to the grid for consumption in region j
hfdiselec_2_fcell$_{j,m}$	kg	Variable for hydrogen fuel produced by both new and old distributed electrolyzers in

		region j in time slice m for storage for later use in a fuel cell
hfdiselec$_j$	kg	Variable for hydrogen fuel produced by both new and old distributed electrolyzers in region j for use as a transportation fuel
HF_DISELEC_CAP$_j$	MW	Variable for new distributed conversion to storage capacity (e.g., electrolyzer/hydrogen storage) powered by the grid and located in region j
HF_DISELEC_CAPOLD$_{j,t}$	MW	The distributed conversion (e.g., electrolyzer) capacity built in period t in region j
hfdold$_j$	Kg	Hydrogen transportation fuel supplied by all remaining hydrogen production facilities built in prior periods
hf_inregion$_{c,hscp,i}$	Kg	Variable for hydrogen fuel produced from class c wind from step hscp in region i for the supply curve that provides the cost of hydrogen fuel shipment from wind in the region to city load centers within the same region i
hf_inregion_cost$_{c,hscp,j}$	$/kg	Cost associated with step hscp for the shipment of hydrogen fuel from a class c wind site within region i to a city within the region
hfs$_i$	kg	A variable for the hydrogen fuel produced in region i from new onshore wind installations that are connected to the grid
hf$_{i,j}$	kg	A variable for hydrogen fuel shipped to region j from new onshore wind installations in region i that are connected to the grid
HF_STEAMREF_CAP$_j$	Kg/year	A variable for new steam methane reformer capacity in region j
HF_STEAMREF_CAPOLD$_{j,t}$	Kg/year	The SMR capacity built in period t in region j
hfsteamref$_j$	kg	A variable for hydrogen fuel produced by both new and old steam methane reformers in region j
H$_m$	Hr	The number of hours in a year in time slice m
HSMRGBIN$_{hsmrbp}$	Kg/year	Variable for new national steam methane reformer capacity in growth bin hsmrbp
HSMRGBINCAP$_{hsmrbp}$	fraction	Fractional growth in national steam methane reformer capacity in growth step hsmrbp
i	integer	Subscript indicating a wind supply region.
i$_c$	fraction	The construction loan interest rate
IDC		Multiplier to capture after-tax value of interest during construction
IL$_n$	MW	Interruptible load in PCA n

$ILGt_{ILG}$		The fraction of peak demand in step ILG of the supply curve
ILGP	fraction	The fractional increase in the cost of interruptible load for each percent increase over the base amount
$ILt_{ilg,n}$	MW	Interruptible load used in PCA n from supply curve step ilg
In	fraction	Nominal interest rate for debt
ind_elec_adder	$/MWh	Additional cost beyond the wholesale cost for delivering grid electricity to distributed electrolyzers and electrolyzers at the wind site
inf	fraction	Inflation rate
I_t		The interest portion of the finance payment made after the loan has been in place t years
ITCW	$	Investment tax credit for wind
$IWSurplus_{c,i,in}$	fraction	Fraction of wind from a class "c" site in region "i" that is supplied to interconnect "in" that cannot be used because there is excess generation
$IWSurplusMar_{c,i,in}$	fraction	The fraction of wind generation lost from the next unit of class c wind installed in region i because there is no remaining load to be met by the wind in interconnect in
$IWSurplusOld_{in}$		The fraction of wind generation lost from all the wind installed to date in interconnect in because there is no remaining load to be met by the wind in interconnect in
j	integer	Subscript indicating a wind supply/demand region
L	years	Loan period
$L_{m,n}$	MW	The load in time slice m in PCA n
$loadgrowth_n$		The annual rate of load growth for PCA n
$lowsulcoalold_{n,q}$	MWh	Variable for the amount of electricity generated from low-sulfur coal in PCA n by coal technology q in the previous 2-year time period
$learnpar_q$	fraction	The learning parameter for wind or the reduction in the capital cost of wind for each doubling of the installed capacity
LP_{pol}	tons/year or lbs/year	The national annual cap on pollutant pol
L_q	years	The economic lifetime of technology q
$ltime_q$		The assumed operational lifetime in years of capacity of type q

LW	years	Lifetime of the wind plant[10]
m	integer	Subscript for the time slice
m' and m''		The shoulder time slices within each season (summer, winter, spring, and fall)
$MINSR_q$	fraction	The fraction of each type of plant q that must be on line and loaded in order to serve as spinning reserve
$M_{n,p}$		Zero-one parameter indicating whether PCAs n and p are within 600 miles of one another
MTDF		Must-run conventional capacity, defined as existing available (i.e., not in a forced outage state) coal and nuclear capacity times a minimum turn down fraction
$MW\_inregion\_dis_{c,escp,j}$	$/MWh	Levelized cost from the escp step of the supply curve for the cost of building a transmission line from a class c onshore wind site to a load center within region i
$MW\_inregion\_disofd_{c,escpofd,j}$	$/MWh	Levelized cost from the escpofd step of the supply curve for the cost of building a transmission line from a class c deep offshore wind site to a load center within region i
$MW\_inregion\_disofs_{c,escpofs,j}$	$/MWh	Levelized cost from the escpofs step of the supply curve for the cost of building a transmission line from a class c shallow offshore wind site to a load center within region i
$NERCRm_r$		Reserve margin requirement in NERC region r
$NOR2_r$		The variance of the usual operating reserve requirement in NERC region r
Norfrac		The normal operating reserve fraction per MW of load
Norhydro		The amount by which the operating reserve can be reduced for each MW of hydroelectricity in the region
NOR_r		Normal operating reserve standard deviation in NERC region r
$numhoursbyseason_s$		Number of hours in season s
$numpeakhoursbyseason_s$		Number of peak hours in season s
$old\_grid\_2\_welectrolysis_{i,m}$		Electricity from the grid in region i consumed in time slice m by wind-sited electrolyzers built in previous periods
$optime_{mm}$		Off-peak time slice mm

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[10] The wind lifetime is used to adjust the capital cost by the ratio of CRF(d,E)/CRF(d,LW) to account for any difference in lifetimes between wind and the economic evaluation period, E.

ordyear	years	Year of the optimization minus 2000 (i.e, the number of years since the beginning of the simulation)
$PCAdmdPK_n$		Peak demand in PCA n in 2000
$PCOSTFRAC_q$	1+fraction	Multiplier on operating/fuel cost associated with the operation of a thermal base-load unit at a higher level during the peak period than in the shoulder periods, e.g. cycling, ramping costs
P_n	MW	Peak load in PCA n
P_t		The principal portion of the finance payment made after the loan has been in place t years
POSTSTWCOST	$/MWh	Cost for transmitting power across a PCA
$PostStamp_{i,j}$	integer	Number of PCAs between wind regions i and j that must be crossed for wind power to be transmitted from i to j
$PostStamp_{n,p}$	integer	Number of PCAs between PCAs n and p that must be crossed for power to be transmitted from n to p
$PRETIRE_{n,q}$		The planned retirement in this period in PCA n of capacity of type q
PTCP	10 / years	Production tax credit period (use 10)
$ptime_m$		A binary constant equal to 1 when m is a peak-load time slice, 0 otherwise
$PVA_{d,E}$		Present value of annual $1 payments for E years
$PVA_{name,d,E,n}$		Present value of annual fuel costs for technology q in PCA n escalating annually for E years
PVDebt		The after-tax present value of debt payments
PVDep		The present value of depreciation
$QS_{n,q}$	MW	A variable for the capacity of type q in PCA n that has been modified to provide quick start capability
$RegDmd_{j,m}$		The electric load in region j in each hour of time slice m in the year 2000
$REMSCHED_{n,q}$		The remaining scheduled planned retirements in future periods in PCA n of capacity of type q
resconfint		Operating reserve minimum expressed in terms of the number of standard deviations of operating reserve required
RPSFrac	fraction	National Renewable Portfolio Standard level expressed as a fraction of annual national electric generation

RPSSCost	$/MWh	Penalty imposed on utilities for not meeting the national RPS requirement
RPS_Shortfall	MWh	A variable for the additional amount of wind generation needed to meet the national RPS requirement beyond that supplied
SMRGR(HSMRBP$_k$)		Breakpoints that discretize the SMR growth price penalty
SMRretper		The period during which the older remaining (i.e not yet retired) SMR were constructed
SR$_{m,n,q}$	MWh	Spinning reserve capacity during time period m in PCA n from technology q
steam_ref_emiss$_{pol}$	tons or pounds	Emissions of pollutant pol per MMBtu of gas input to steam methane reforming
ST_RPSSCost$_{states}$	$/MWh	Penalty imposed on utilities for not meeting the RPS requirement in states
ST_RPS_Shortfall$_{states}$	MWh	A variable for the additional amount of wind generation needed to meet the RPS requirement beyond that supplied in states
T_delay		The time required for learning to impact the market, i.e. the learning delay in periods between installations and cost reductions
TLOSS	fraction	Fraction of conventional power lost in each mile of transmission
Tk	MW	Capacity of transmission line k
TNCost	$/MW-mile	Cost of new transmission lines
TNWCost	$/MW-mile	Cost of new wind transmission lines
TOCost	$/MWh-mile	Cost of transmission on existing lines
TOWCost	$/MWh-mile	Cost of wind transmission on existing lines
TPCA_CG$_{tpca\_g}$	$/MW-mile	Difference between the price and cost of new transmission, due to rapid growth in transmission installations
TPCA_Ct$_{tpca\_g}$	MW	A variable for the new transmission capacity in growth bin tpca_g
TPCA_Gt$_{tpca\_g}$		A fractional multiplier of the national transmission (MW) capacity BASETPCA used to establish the size of growth bin tpca_g
TPCA_GP		The percent increase in the cost of transmission for each percent growth over the base amount
TPCAN$_{n,p}$	MW	New transmission line capacity built to carry new generation between PCA n and PCA p
TPCAO$_{n,p}$	MW	The transmission capacity between n and p that existed at the start of the period.
TR	fraction	Combined federal and state income tax rate

TR_j	MW	Capacity of transmission lines crossing the boundaries of wind supply region j
TWLOSS	fraction	The fraction of wind power lost in each mile of transmission.
$VCcoal_{n,q}$		The variable cost of operating a coal plant of type q in PCA n this period
WCC_c	\$/MW	The overnight capital cost of a class c wind plant
WCt_g	MW	A variable for new onshore national wind turbine capacity in bin g; used for estimating the increase in wind turbine price with rapid world growth
$WCtinst_{ginst,i}$	MW	A variable for new onshore wind turbine capacity from bin ginst in region i; used for estimating the increase in installation costs with rapid regional growth
$WCVmar_{c,i,r}$	fraction	(Wind Capacity Value – marginal) The effective load-carrying capacity of 1 MW at a new wind farm at a class c site in region i delivered to NERC region r
$WCVold_r$	fraction	(Wind Capacity Value – old) The effective load-carrying capacity of all the wind capacity installed in previous periods whose generation is transmitted to NERC region r
$WELEC\_inregion_{c,escp,i}$	MW	A variable for new onshore wind turbine capacity from a class c wind site within region i from step escp of the supply curve for transmission costs that is transmitted on new transmission lines to a load center also within region i
$WELEC\_inregionofd_{c,escpofd,i}$	MW	A variable for new deep offshore wind turbine capacity from a class c wind site within region i from step escpofd of the supply curve for transmission costs that is transmitted on new transmission lines to a load center also within region i
$WELEC\_inregionofs_{c,escpofs,i}$	MW	A variable for new shallow offshore wind turbine capacity from a class c wind site within region i from step escpofs of the supply curve for transmission costs that is transmitted on new transmission lines to a load center also within region i
$wind\_2\_electrolysis_{c,i,s}$	MWh	A variable for class c onshore wind generation from new wind turbines that connect to the grid (not directly to load-distribution systems) supplied to a new

		conversion to storage process (e.g., electrolyzer/hydrogen storage) in region i in season s
wind_2_electrolysis_inregion$_{c,i,s}$	MWh	A variable for onshore wind-generated electricity in season s from class c new turbines in region i that goes to storage (e.g., electrolyzer/hydrogen storage) at a wind site that is not connected to the grid, but is connected by new lines directly to the distribution system at a load center
WindCap$_{T\_delay}$		The total national installed wind capacity T_delay periods ago
WN$_{i,j}$	MW	A variable for new onshore wind turbine capacity in region i that is transmitted to region j by connecting to the existing transmission grid
WNofd$_{i,j}$	MW	A variable for new deep offshore wind turbine capacity in region i that is transmitted to region j by connecting to the existing transmission grid
WNofs$_{i,j}$	MW	A variable for new shallow offshore wind turbine capacity in region i that is transmitted to region j by connecting to the existing transmission grid
WNSC$_{i,wscp}$	MW	A variable for new onshore wind turbine capacity to be connected to the grid in region i from step wscp of the supply curve, which provides the cost of building transmission from region i to the grid
WNSCofd$_{i,wscpofd}$	MW	A variable for new deep offshore wind turbine capacity to be connected to the grid in region i from step wscpofd of the supply curve, which provides the cost of building transmission from region i to the grid
WNSCofs$_{i,wscpofs}$	MW	A variable for new shallow offshore wind turbine capacity connected to the grid in region i from step wscpofs of the supply curve, which provides the cost of building transmission from region i to the grid
WO$_{c,i,j}$	MW	Existing (from the preceding time period) class c onshore wind on existing (at start of the simulation) transmission lines from region i to region j
WOofd$_{c,i,j}$	MW	Existing (from the preceding time period) class c deep offshore wind on existing (at start of the simulation) transmission lines

		from region i to region j
WOofs$_{c,i,j}$	MW	Existing (from the preceding time period) class c shallow offshore wind on existing (at start of the simulation) transmission lines from region i to region j
WOMF$_c$	$/MW-yr	Fixed annual O&M cost of class c wind
WOMV$_c$	$/MWh	Variable operating cost of class c wind
wor2factor		A multiplier on the wind variance to provide the appropriate impact on operating reserve requirements
WORmar$_{c,i,r}$		The operating reserve requirement induced by the marginal addition of one MW of class c wind in region i that is consumed in NERC region r
WORold$_{c,r}$		The average operating reserve induced per MW of existing class c wind that is consumed in NERC region r
WORold$_r$		The operating reserve requirement induced by all wind installed in previous periods that contributes to NERC region r
WPTC	$/MWh	Wind federal production tax credit
WR2G$_{c,i,wscp}$	MW	New onshore class c wind resource in region i available at interconnection cost step wscp
WR2Gofd$_{c,i,wscpofd}$	MW	New deep offshore class c wind resource in region i available at interconnection cost step wscpofd
WR2Gofs$_{c,i,wscpofs}$	MW	New shallow offshore class c wind resource in region i available at interconnection cost step wscpofs
WR2GPTS$_{c,i,wscp}$	$/MW	Cost of building transmission interconnect to the grid for class c onshore wind resource in region i in supply curve step wscp
WR2GPTSofd$_{c,i,wscp}$	$/MW	Cost of building transmission interconnect to the grid for class c deep offshore wind resource in region i in supply curve step wscpofd
WR2GPTSofs$_{c,i,wscp}$	$/MW	Cost of building transmission interconnect to the grid for class c shallow offshore wind resource in region i in supply curve step wscpofs
WROW		The wind capacity installed in the rest of the world T_delay periods ago
WRUC$_{c,i}$	MW	Class c onshore wind resource in region i
WRUCofd$_{c,i}$	MW	Class c offshore deep wind resource in region i
WRUCofs$_{c,i}$	MW	Class c offshore shallow wind resource in

		region i
$WS_{j,m}$	MW	A variable for the amount by which the wind power supplied to region j exceeds the electricity demand in region j in time slice m
$WT_{n,p}$	MW	A variable for the new wind transmitted from PCA n to PCA p[11]
$WTN_{i,j}$	MW	A variable for new onshore wind capacity in region i that is transmitted to region j by a new transmission line built for and dedicated to wind transmission
$WTNofd_{i,j}$	MW	A variable for new deep offshore wind capacity in region i that is transmitted to region j by a new transmission line built for and dedicated to wind transmission
$WTNofs_{i,j}$	MW	A variable for new shallow offshore wind capacity in region i that is transmitted to region j by a new transmission line built for and dedicated to wind transmission
$WTO_{c,i,j}$	MW	Existing (at start of this time period) class c onshore wind on new transmission lines from region i to region j
$WTOofd_{c,i,j}$	MW	Existing (at start of this time period) class c deep offshore wind on new transmission lines from region i to region j
$WTOofs_{c,i,j}$	MW	Existing (at start of this time period) class c shallow offshore wind on new transmission lines from region i to region j
$Wtur\_inregion_{c,i}$	MW	A variable for new onshore wind turbine capacity whose transmitted electricity will move on new transmission lines dedicated to wind from a class c wind site within region i to a load center also within region i
$Wtur\_inregionofd_{c,i}$	MW	A variable for new deep offshore wind turbine capacity whose transmitted electricity will move on new transmission lines dedicated to wind from a class c wind site within region i to a load center also within region i
$Wtur\_inregionofs_{c,i}$	MW	A variable for new shallow offshore wind turbine capacity whose transmitted electricity will move on new transmission lines

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[11] Without this variable, WinDS will ship power from wind supply region i to the closest wind demand region j; and, from there, continue to ship it as conventional power to other PCAs where generation is needed. The problem with this is that if new lines are required for this extended wind transmission to a different PCA, the wind will not have to pay for a dedicated transmission line, i.e. the transmission line cost will be spread over more hours than only those during which the wind blows.

		dedicated to wind from a class c wind site within region i to a load center also within region i
$WturN_{i,wscp}$	MW	A variable for new onshore wind turbine capacity able to be connected to existing transmission lines from region i at a cost associated with step wscp of the transmission supply curve
$WturNofd_{i,wscpofd}$	MW	A variable for new deep offshore wind turbine capacity able to be connected to existing transmission lines from region i at a cost associated with step wscpofd of the transmission supply curve
$WturNofs_{i,wscpofs}$	MW	A variable for new shallow offshore wind turbine capacity able to be connected to existing transmission lines from region i at a cost associated with step wscpofs of the transmission supply curve
$WturO_{c,i}$	MW	Existing ("O"ld) (from the preceding time period) class c onshore wind transmitted on existing lines from region i
$WturOofd_{c,i}$	MW	Existing ("O"ld) (from the preceding time period) class c deep offshore wind transmitted on existing lines from region i
$WturOofs_{c,i}$	MW	Existing ("O"ld) (from the preceding time period) class c shallow offshore wind transmitted on existing lines from region i
$WTturO_{c,i}$	MW	Existing ("O"ld) (from the preceding time period) class c wind transmitted on new transmission lines from region i
$WTturOofd_{c,i}$	MW	Existing ("O"ld) (from the preceding time period) deep offshore wind on new transmission lines
$WTturOofs_{c,i}$	MW	Existing ("O"ld) (from the preceding time period) shallow offshore wind on new transmission lines
$WturTN_i$	MW	A variable for new onshore wind turbine capacity that can be transmitted only on new transmission lines dedicated to wind transmission from region i to another region
$WturTNofd_i$	MW	A variable for new deep offshore wind turbine capacity that can only be transmitted on new transmission lines dedicated to wind transmission from region i to another region
$WturTNofs_i$	MW	A variable for new shallow offshore wind turbine capacity that can only be transmitted

		on new transmission lines dedicated to wind transmission from region i to another region
W_UScapyr2000		The total national wind capacity in the year 2000
γ	1.96	Confidence interval parameter (95%)